WDM Component Requirements for Bit-Parallel Fiber Optic Computer Networks

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Abstract

The device specifications for an all optical bit-parallel WDM single fiber link for the cluster computer network community are intended for dissemination to the opto-electronic device research community to stimulate synergy between the two, ultimately leading to early availability of new devices to the computer network researchers. It is also hoped that early adoption of these devices by the research community will promote limited production of these devices by industry. Background information on our investigation of this problem will first be given. Then the detailed design of a long distance (32 km) all optical bit-parallel WDM single-fiber link with 12 bit-parallel channels having 1 Gbytes/sec capacity is given. The speed-distance product for this link is 32 Gbytes/sec-km. Means to improve this speed-distance product using the pulse shepherding effect will be described. Finally, a detailed description of the BP-WDM component requirements is given.

Keywords: Wavelength division multiplexed propagation, nonlinear pulses, solitons, bit-parallel link.

I. Background and Introduction

Unlike the usual wavelength division multiplexed (WDM) format where input parallel pulses are first converted into a series of single pulses which are then launched on different wavelength beams into a single-mode fiber, the bit-parallel (BP) WDM format was proposed [1,2]. Under this BP-WDM format, no parallel to serial conversion of the input signal is necessary, parallel pulses are launched simultaneously on different wavelength beams. Time alignment of the pulses for a given signal byte is very important.

There exists a competing non-WDM approach to transmit parallel bits - the fiber optic ribbon approach - where parallel bits are sent through corresponding parallel fibers in a ribbon format. However, it is very difficult to maintain time alignment of the parallel pulses due to practical difficulty in manufacturing identical uniform fibers. Furthermore, it is known that computer vendors would like to apply the same technology to increase the bandwidth of campus network in support cluster computing, and to provide salable external I/O networks for clusters of massively parallel processor (MPP) supercomputers (i.e., multiple network channels connected to one machine). Cluster computing is expected to gain greater importance in the near future as users tap the latent unused computer cycles of company workstations (sometimes in off hours) to work on large problems, rather than buying a specific supercomputer. In DoD applications, it would enable high performance computers to be deployed in embedded systems.

For high performance computing environments, clusters of MPP supercomputers can also be envisioned. This concept elevates the cluster computing model to a new level. In this case, not only is high bandwidth and low latency required, but now inter-channel message synchronization also becomes important among the parallel network channels entering the machine - especially if all machines are tightly coupled together to work on one large problem. In the limit, the aggregate bandwidth required to interconnect two large MPP supercomputers approaches the bisection bandwidth of the internal communication network of the machine. For example, in a 2^n-node hypercube interconnected MPP architecture, there would be up to 2^{n-1} links between each half of the machine (e.g., 1024 processor nodes would have 512 links at 200MB/s per link, or 102 GB/s total).

The need for a single media parallel interconnect is apparent. Thus, the single fiber WDM format of transmitting parallel bits rather than a fiber ribbon format may be the media of choice. This single fiber bit parallel wavelength link can be used to extend the (speed-distance) product of emerging cluster computer networks, such as, the MyriNet, SCI, Hippi-6400, ShuffleNet, etc.

As an example, the detailed design of a long distance (32 km) all optical bit-parallel WDM single-fiber link with 12 bit-parallel channels having 1 Gbytes/sec capacity using available components and fiber will first be presented. The speed-distance product for this link is 32 Gbytes/sec-km while the maximum speed-distance product for fiber ribbon is less than 100 Mbytes/sec-km.

Then, to demonstrate the viability of this link, two WDM channels at wavelengths 1530 nm and 1545 nm carrying 1 ns pulses on each channel were sent through a single 25.2 km long Corning DS fiber. The walkoff was 200 ps, well within the allowable setup and hold time for the standard ECL logic which is 350 ps for a bit period of 1 ns.

To further improve the speed-distance product of a single fiber link under the BP-WDM format, more stringent time alignment for shorter pulses must be achieved. Recently, we have discovered a pulse shepherding effect which may be used to enhance this pulse alignment along the fiber [3]. A brief discussion of this effect will be given below. The development of a DS type fiber with improved group velocity dispersion characteristics is also desired.

Finally, a detailed description of the BP-WDM component requirements will be given.

II. Elements of a 12 Bit-Parallel WDM System

Consider now the design of our BP-WDM system. Due to the relatively broad pulse-widths (1 ns) and low power levels of the data pulses, nonlinear interaction of co-propagating pulses can be consider to be negligible [3]. It is expected that 12 separate beams will be used. Anticipating the use of erbium amplifier, beam separation among these 12 beams must be limited by the useful bandwidth of the erbium amplifier which is from 1535 nm to 1560 nm. Hence, separation between neighboring beams must be less than 25/12 = 2.08 nm or 2 nm. A block diagram of the link is shown in Fig. 1.

The Transmitter

The transmitter of the system consists of 12 discreet distributed-feedback laser diodes and a 16-to-1 fiber coupler. Each laser element is selected to fall within the erbium gain bandwidth at a pre-selected Dl from its neighbors. To minimize system cost, the lasers are directly modulated with NRZ data at a rate up to 1 Gbits/sec each, for an aggregate of 1 Gbytes/sec. The timing of the bits in any word are aligned at the input to the fiber link by adjusting the phase of the laser drive signal for each bit using conventional electrical delay components. The optical power coupled into the fiber arms at the input to the 16-to-1 coupler is about 0 dBm (i.e., 1 mW).

The Single-Mode Fiber

Corning DS fiber is chosen to be the single-mode fiber for this system because of its desirable dispersion characteristics [4]. One notes that for the wavelength range of interest (1535 nm to 1560 nm), the dispersion coefficient, $|\beta_2|$, is around 2 ps^2/km. The difference of group velocities as a function of the wavelength of the beams have been measured and are displayed in Fig. 2. It is seen that the maximum difference in group velocity over the wavelength of interest is 5 ps/km. An erbium-doped fiber amplifier (EDFA) is used to boost the power at the receiver.

The Receiver

The receiver of the system consists of a 1-to-16 fiber splitter, 12 optical bandpass filters, and 12 fiber optic receivers.

III. Design Considerations

Wavelength Spacing Consideration

At 1 Gbytes/sec, each bit path must have a minimum bandwidth of 2 GHz to reproduce the data. In estimating the spread of the optical spectrum of each laser element, a 4 GHz bandwidth will be assumed. The spread of each element's spectrum, $\Delta\lambda$, is then 0.032 nm for a 4 GHz bandwidth which is well within the 2 nm beam separation between neighboring beams. It should be noted that any spectral broadening of the pulse due to chirp or other factors will be much less than the 2 nm beam separation that has been used for our system. Furthermore, the 2 nm beam separation also lessens the demand on the optical bandpass filters used to separate the WDM beams at the receiver end.

Skew and Walk-Off Consideration

At 1 Gbits/sec, the bit period is approximately 1 ns. For the worst case, the setup and hold time for standard ECL logic is 350 ps. This means that there is a leeway of (1000-350)/2 = 325 ps in which the pulses may drift away from each other. If one limits the skew or walkoff to half of 325 ps, then the maximum length of fiber which can be used is 160/5 = 32 km.

Loss Consideration

For a maximum length of 32 km, it is clear that an EDFA will be needed to increase the power at the receiver. As indicated in Fig. 1, a gain of 20 dB via the EDFA will provide a gain margin of more than 12 dB at the receiver.

IV. Experimental Demonstration Of A Two Wavelengths BP-WDM System

The experimental setup is shown in Fig. 3. Two beams from two laser diodes whose wavelengths are 1530 nm and 1545 nm, are modulated by nano-second size pulses. These beams are coupled simultaneously into a Corning DS fiber. A picture of the pulses on these two beams before they were launched into the fiber is shown in Fig. 4(a). It is seen that these nano second size pulses were well aligned at the entrance of the fiber link.

The spool of Corning DS fiber used for our experimental link was 25.2 km long. The output was displayed in Fig. 4(b). One can readily measure the shift or the walkoff between these pulses - it was 200 ps or 6 ps/km. This result is consistent with our previous measurement displayed in Fig. 2. There, the walkoff was measured between a tunable ring laser and a 1545 nm laser diode.

It is noted that the experimentally measured walkoff of 200 ps for this two wavelength BP-WDM demonstration is well within the allowable setup and hold time for the standard ECL logic which is 350 ps for a bit period of 1 ns.

We have shown through an actual experiment that nanosecond size pulses on two BP-WDM beams at 1530nm and at 1545 nm can be successfully transmitted through a 25.2 km long Corning DS fiber with acceptable walkoff which is well within the allowable setup and hold time of standard ECL logic circuits. As can be seen from Fig. 3 that the maximum walkoff between any beams located within the wavelength range of 1530nm and 1560 nm is 200 ps. This result implies that 30 bit-parallel beams spaced 1 nm apart from 1530 nm to 1560 nm, each carrying 1 Gbits/sec signal, can be sent through a 25.2 km Corning DS fiber at an information rate of 30 Gbits/sec. This means that the speed-distance product for this link is about 94 Gbytes/sec-km, a number way beyond the best that fiber ribbon can offer.

V. The Shepherding Effect

It is seen that in order to further improve the speed- distance product in a single fiber, even better time alignment of the WDM pulses must be required. We have found that significant improvement in pulse alignment may be obtained when the shepherding effect is introduced.

In a WDM system, the cross phase modulation (CPM) effects [3,5] caused by the nonlinearity of the optical fiber are unavoidable. These CPM effects occur when two or more optical beams co-propagate simultaneously and affect each other through the intensity dependence of the refractive index. This CPM phenomenon can be used to produce an interesting pulse shepherding effect.

The fundamental equations governing M numbers of co-propagating waves (including the large amplitude shepherd wave) in a nonlinear fiber including the CPM phenomenon are the coupled nonlinear Schrodinger equations [3,5]:

$$\frac{\partial A_j}{\partial z} + \frac{1}{v_{gj}}\frac{\partial A_j}{\partial t} + \frac{1}{2}\alpha_j A_j = \frac{1}{2}\beta_{2j}\frac{\partial^2 A_j}{\partial t^2} - \gamma_j\left(|A_j|^2 + 2\sum_{m\neq j}^{M}|A_m|^2\right)A_j$$

$$(j = 1,2,3, \cdots\cdots M) \qquad (1)$$

Here, for the jth wave, $A_j(z,t)$ is the slowly-varying amplitude of the wave, v_{gj}, the group velocity, β_{2j}, the dispersion coefficient ($\beta_{2j} = dv_{gj}^{-1}/d\omega$), α_j, the absorption coefficient, and

$$\gamma_j = (n_2 \omega_j)/(c A_{eff}) \quad (2)$$

is the nonlinear index coefficient with A_{eff} as the effective core area and $n_2 = 3.2 \times 10^{-16}$ cm^2/W for silica fibers, ω_j is the carrier frequency of the jth wave, c is the speed of light, and z is the direction of propagation along the fiber.

Solution of these coupled nonlinear equations will provide information on how a large amplitude shepherd pulse can influence the propagation behavior of all the co-propagating data pulses (the shepherding effect).

An initial example of the pulse shepherding effect [5] is shown below:

Let us assume that two gaussian pulses on two different wavelength beams with wavelengths of 1.55 μm and 1.546 μm, originating in an aligned position as shown in Fig. 5(a), begin to separate from each other due to slight difference in the group velocities for these two beams. Without the presence of a shepherd pulse, these beams will be approximately 1/2 pulsewidth apart at 50 km downstream as can be seen from Fig. 5(a). With the shepherd pulse of $2 \exp(-0.5\ t^2)$ on a third beam with wavelength 1.542 μm, originally aligned with the two shepherded pulses and propagating at the same velocity as the pulse on beam #1, at 50 km downstream, the shepherded pulses are still aligned as shown in Fig. 5(b).

Due to the nonlinear self-phase modulation (SPM) and cross phase modulation (CPM) effects, the pulses tend to attract each other. They appear to congregate towards region of higher induced index of refraction. The forward pulse is pulled back while the backward pulse is pushed forward so that these pulses tend to align with each other. This observation is consistent with earlier discovery of the self-focusing effect where the induced higher refraction index region caused by higher beam intensity tends to 'attract' the propagating optical wave, resulting in the 'focusing' of this optical wave. It is also consistent with the concept used to confine thermally-bloomed high-energy laser beam, where multiple surrounding beams are used to create an index environment in which the central main beam tends to expand less due to the lowering of the surrounding index of refraction caused by the heating from the surrounding beams [6].

What this means is that through the introduction of a shepherd pulse on a separate wavelength beam, it appears to be possible to dynamically manipulate, control and reshape pulses on co-propagating beams in a WDM system. This dynamic control feature from a shepherd pulse will enable the eventual construction of a time-aligned bit-parallel wavelength link as an interconnect with exceptionally high speed, low latency, simplified electronics interface (with no speed bottleneck), and extendibility to all-optical packet networks.

It should be noted that, due the the complicated nonlinear interaction effect, adding strength or sharpness of the shepherding pulse does not necessarily provide tighter or longer shepherding effect for all the data pulses. This is because high magnitude and narrow shepherd pulse tends to breakup into several oscillating pulses, thereby diminishing the pulse shepherding effect. Future research will be aimed at finding the optimum shepherding condition as well as finding the limitations of this shepherding effect.

VI. BP-WDM Component Requirement

The following device specifications of the ShuffleNet cluster computer network are intended for dissemination to the opto-electronic device research community to stimulate synergy between the two, ultimately leading to early availability of new devices to the computer network researchers. It is also hoped that early adoption of these devices by the research community will promote limited production of these devices by industry.

Three phases of development is envisioned: Phase 1 has direct modulated array sources with 4 elements operating at 1.6 Gbit/s without the use of shepherd pulse for alignment. Phase 2 has external modulated array sources with 4 elements operating at 8 Gbit/s without the use of shepherd pulse for alignment. Phase 3 has external modulated array sources with 10 elements operating at 20 Gbit/s with shepherd pulse for alignment.

1. Transmitter Specifications

For communication link speeds above 10 Gbit/s, it becomes progressively more desirable to use external modulators in the transmitter to reduce chirp (for DC operated laser diode sources) or to gate very fast periodic pulses (for mode locked laser diode sources). The highest link speeds can be obtained with mode locked sources, ranging from 20 Gbit/s RZ per wavelength to perhaps 100-200 Gbit/s. For the BPW Phase 3 link, 20 GHz modulator would be required per wavelength channel. Array sizes should be no smaller than 10 (with 12 being optimum). Finally, the most difficult challenge will be the modulator drive voltage. As speeds increase, typically the drive voltage requirement also increases for modulator technologies. Unfortunately, in general, the drive voltage and power of electronics decreases with increasing frequency making it progressively more difficult to drive the modulator with simple logic circuits typical of network host interfaces. For this reason, and the fact that there are many complex design tradeoffs between the modulator design and electronic drive circuit, we shall assume that a suitable driver will be provided with the modulator to provide proper bias and signal voltage/current amplitude from a 5 volt standard logic signal.

Modulator Bank Specifications §	
Commercial Laser arrays	2.5 GHz at ~1.55
Present Devices	20 GHz, 1-2 volts
The spacing between the lasers in the array	250 microns
For Lower speed operation (~2.5 GHz): For higher speed operation (~2.5 GHz and up):	modulating the current is sufficient and there is no need for external modulators external modulators are needed.
Chirp is a problem for high speed operation	but can be solved by using external modulators.
The gain bandwidth of the amplifiers	~20 nm, which limits the number channels (wavelengths).
The channel spacing	either 100 GHz or 200 GHz.
Modulator Requirement:	Either Mach-Zehnder or directional coupler can be used.
Extinction ratio (optical):	25 dB
Cross Talk (electrical):	30 dB
Operating Voltage§§:	~5 volts
Intensity Linearity	up to 50 milliwatts
Add/Drop Filter: Wavelength (l) Spacing: Phase II Phase III Cross-talk: Insertion Loss: Device Length:	10 channel with fiber pigtail 3.2 nm 3.2 nm 200 GHz or 1.6 nm -30 dB to -35 dB down < 5dB unspecified polarization insensitive

§ This specification is not required for any system at any particular time, but provides a system-driven goal.
§§It is desirable that the operating voltage be 3 volts or less, but for $LiNbO_3$ its will be 10-20 volts and for polymers, the lower limit is 5 volts (but depends on device length).

Comments: The power range should be able to handle a soliton pulse. Phase 2 can use the commercial laser arrays and Phase 3 uses the Shepherd pulse.

Transmitter Device: Source Phase I

The purpose of the laser diode source array is to provide a variety of stepped wavelengths, either direct modulated (Phase 1) or external modulated (Phase 2 and 3) in the 1550nm band. In Phase 1, each laser diode should be capable of being direct modulated for SONET OC-48 links, nominally about 2.5Gbit/s. In Phase 2, each device in the four-element laser diode array is individually mode locked at 20GHz with a pulse wide not to exceed 15ps. It is assumed that an external modulator array will be used to impress data on each channel. For Phase 3, the array size is increased to 10 minimum (12 maximum) to support byte transmission with an external modulator array for the final BPW link. If an integrated coupler is not provided on-chip, the supplier should provide a suitable external 10:1 (12:1) coupler for coupling all channels into one fiber.

Specifications of the four channel WDM source†		
1.	Emission wavelengths of DFB lasers ††: channel 1. channel 2: channel 3: channel 4:	1549.32 nm 1552.52 nm* 1555.75 nm 1558.99 nm *(the reference of 193.1 Thz.)
2.	SMSR under 40 mA peak-to-peak modulation and 8.2 dB extinction ratio (SONET OC-48 spec.)	> 30 dB
3.	Threshold current	< 30 mA
4.	External efficiency	>0.2 mW/mA
5.	Fundamental transverse mode operation up to IDC	100 mA
6.	Power coupled into single mode fiber @100 mA	> +6.0 dBm
7.	Modulation bandwidth	2.5 Gb/s †††
8.	Four ECL inputs to drivers	25 W
9.	Four single mode outputs, optical isolator in each laser package.	
10.	Back facet monitor in each laser package	
11.	Front panel setting of laser bias current and temperature for each laser	
12.	Front panel indicator lights to indicate operation of each laser	

† A prototype has met all of these specs and the accuracy of each channel wavelength is better than 0.1 nm. SMRS on all four lasers is better than 35 dB and the spectra are very clean. The system takes about 3 minutes to warm up and reach the specified wavelengths.
†† All channel wavelengths to be accurate to 0.3 nm. All wavelengths and spectral properties measured at a chip power output of 5 mW. The wavelength may be trimmed with a TC cooler, as long as other specs are maintained
††† Modulation bandwidth is limited by the driver chip.

Transmitter Device: Source Phase II

Specifications for Mode-Locked Lasers for WDM Applications (4 Channels without Shepherd Pulse)		
1.	Power (at facet)	> 1 mW
2.	Pulsewidth	< 15 ps
3.	Dn * Dt (assume sech^2)	< 1
4.	Repetition rate	17.5 - 20 GHz
5.	Wavelength	1535 - 1565 nm
6.	Wavelength Spacing	nominally 3.2 nm (3-4 nm)
7.	Operating Current (DC) (total = Gain + Grating)	< 300 mA/device
8.	Operating Voltage (DC) (Saturable Absorber)	< -3.0 V
9.	RF Power (Saturable Absorber)	< 20 dBm/device
10.	External Efficiency (4.3 mm device)	> 8%
11.	Threshold Current (DC) (total = Gain + Grating)	< 200 mA
12.	Number of Elements	4

Transmitter Device: Source Phase III

Specifications for Mode-Locked Lasers for WDM Applications (10-12 Channels without Shepherd Pulse)		
1.	Power (at facet)	> 1 mW
2.	Pulsewidth	< 15 ps
3.	Dn * Dt (assume $sech^2$)	< 1
4.	Repetition rate	17.5 - 20 GHz
5.	Wavelength	1535 - 1565 nm
6.	Wavelength Spacing	nominally 1.6 nm
7.	Operating Current (DC) (total = Gain + Grating)	< 300 mA/device
8.	Operating Voltage (DC) (Saturable Absorber)	< -3.0 V
9.	RF Power (Saturable Absorber)	< 20 dBm/device
10.	External Efficiency (4.3 mm device)	> 8%
11.	Threshold Current (DC) (total = Gain + Grating)	< 200 mA
12.	Number of Elements	10

2. Receiver Specifications

The 10-12 element WDM receiver array is designed with an integrated filter to properly separate with WDM channel and direct it to the proper detector. The array sizes are 4, 4, and 10-12 for Phases 1 through 3, respectively. The bit rates range from 1.6 Gbit/s to 20 Gbit/s (RZ=15ps). Phase 3 may require either 100GHz amplifier bandwidth or special optical pulse stretching in the front end. The most challenging design parameter will be to keep inter-channel crosstalk from EMI to a minimum, and to preserve the time alignment of the pulses across all channels. As with the transmitter, an integrated coupler and filter is desired, or should be provided as a separate external element.

Receiver Specifications				
		Phase 1	Phase 2	Phase 3
1.	Array Dimension	4	4	12*
2.	Channel Bit Rate	1.6 Gbit/s	8.0 Gbit/s	20 Gbit/s
3.	Bandwidth	5 GHz	5 GHz	100 GHz
4.	Sensitivity	-22 dBm	-22 dBm	-15 dBm
5.	Wavelength Selectivity	5 nm	2 nm	2 nm
6.	Wavelength Crosstalk	-20 dB	-20 dB	-20 dBm
7.	Pulse Reponse	500 ps	125 ps	10 ps
8.	Saturation	0 dBm	0 dBm	20 dBm
9.	Wavelength Band	1530-1565 nm	1530-1565 nm	1530-1565 nm
10.	Spectral Bandwidth	< 50 MHz	< 50 MHz	< 1 MHz
11.	Packaging	discrete	hybrid or monolithic	monolithic
12.	Delivery Date	?	?	?

* NOTE: *10 wavelengths are satisfactory for Myrinet. 12 are needed for HIPPI-6400*

3.0 Switching Equipment Specifications (ShuffleNet Optic Switching Node Specifications)

The Shufflenet optical switch is the key element for implementing a deflection routed network. In Phase 1 (3.1.1), the speeds are low enough (1.6 Gbit/s NRZ per channel) that electronics may be used to implement the node. It is assumed that each optical channel is completely regenerated after passing through each node. In Phase 2, the speeds increase to 8 Gbit/s NRZ per channel . In this case, an optical switch is used with a electronic regenerator on the output. Finally, in Phase 3, 20 Gbit/s RZ rates are achieved with an all-optical switch and regenerator. In each case, progressively flatter spectral and pulse response is required along with tighter WDM channel time alignment in the later phases. For acceptance testing, each node must pass through a sustained loopback test that is equivalent to ten times the worse case maximum number of roundtrips in the shufflenet network.

ShuffleNet Optic Switching Node Specifications Phase 1

ShuffleNet Optic Switching Node Specifications Phase 1: 1.6 Gbit/s System (hybrid e/o) (Mainly electronic)		
1.	Switch Functionality	6 x 6 non-blocking (2 in, 2 out, local; 2 in, 2 out, distant; 2 in, 2 out, storage; all full bandwidth)
2.	Switching Rate	200 MHz
3.	Channel Data Rate	1.6 Gbit/s NRZ
4.	Setup Time	20 ns
5.	Pulse Skew between outputs	100 ps
6.	Pass Through Delay	10 ns
7.	Wavelength	1530 - 1565 nm
8.	Optical Power Range	OUTPUT: 0 dBm +/- 0.1 dB INPUT: no lower than crosstalk (eg -15 dBm)
9.	Optical Taps	One for each input (10%) One for each output (5%)
10.	Maximum Insertion Loss	15 dB
11.	Maximum Channel Crosstalk	15 dB
12.	Minimum Extinction Ratio	20 dB
13.	Optical Coupling Loss	2 dB max
14.	Spectral Flatness	n/a
15.	Cable Connectors	Quick disconnect
16.	Drive Voltage	5 volts (or provide own driver amps to 5 v)
17.	Temperature Range	15 - 22 deg C
18.	Humidity	30-50%
19.	Acceptance Test	2 hour loopback cycling through ports dummy non-sync pseudo random data sent on other channels
20.	Delivery Date	10 units by Jan 1, 1998 (for SSDC testbed) 10 units by Jun 1, 1998 (for NRL testbed)

ShuffleNet Optic Switching Node Specifications Phase 2

ShuffleNet Optic Switching Node Specifications Phase 2: - 8 Gbits/s System (hybrid e/o)		
1.	Switch Functionality	6 x 6 non-blocking (2 in, 2 out, local; 2 in, 2 out, distant; 2 in, 2 out, storage; all full bandwidth)
2.	Switching Rate	500 MHz
3.	Channel Data Rate	8 Gbit/s NRZ (5.0 Ghz analog)
4.	Setup Time	4 ns
5.	Pulse Skew between outputs	20 ps
6.	Wavelength pulse skew	20 ps
7.	Pass Through Delay	10 ns
8.	Wavelength	4 channels max from1530 - 1565 nm
9.	Optical Power Range	OUTPUT: 0 dBm +/- 0.1 dB

		INPUT: no lower than crosstalk (eg -15 dBm)
10.	Optical Taps	One for each input (10%) One for each output (5%)
11.	Maximum Insertion Loss	15 dB
12.	Maximum Channel Crosstalk	15 dB
13.	Minimum Extinction Ratio	20 dB
14.	Optical Coupling Loss	2 dB max
15.	Spectral Flatness	suggest 3 dB max
16.	Cable Connectors	Quick disconnect
17.	Drive Voltage	1.5 volts max (or provide own driver amps to 1.5 v)
18.	Temperature Range	15 - 22 deg C
19.	Humidity	30-50%
20.	Acceptance Test	2 hour loopback cycling through ports dummy non-sync pseudo random data sent on other channels
21.	Delivery Date	20 units by Jan 1, 1999 (for SSDC & NRL testbeds)

ShuffleNet Optic Switching Node Specifications Phase 3

ShuffleNet Optic Switching Node Specifications Phase 3: 20 Gbit/s System (All optical)		
1.	Switch Functionality	6 x 6 non-blocking (2 in, 2 out, local; 2 in, 2 out, distant; 2 in, 2 out, storage; all full bandwidth)
2.	Switching Rate	10 GHz
3.	Channel Data Rate	20 Gbit/s RZ per wavelength (100 Ghz analog) Must transport 10 ps soliton in 2 hr test
4.	Setup Time	4 ns max
5.	Pulse Skew between outputs	5 ps max
6.	Pass Through Delay	10 ns max
7.	Wavelength	12 channels max from 1530 - 1565 nm
8.	Optical Power Range	OUTPUT: 0 dBm +/- 0.1 dB INPUT: no lower than crosstalk (eg -15 dBm)
9.	Optical Taps	One for each input (10%) One for each output (5%)
10.	Maximum Insertion Loss	15 dB
11.	Maximum Channel Crosstalk	15 dB
12.	Minimum Extinction Ratio	20 dB
13.	Optical Coupling Loss	2 dB max
14.	Spectral Flatness	suggested 3 db max †
15.	Cable Connectors	Quick disconnect
16.	Drive Voltage	1 volt max (or provide own driver amps to 1 v)
17.	Temperature Range	15 - 22 deg C
18.	Humidity	30-50%
19.	Acceptance Test	2 hour loopback cycling through ports; dummy non-sync pseudo random data sent on other channels and wabvelengths.
20.	Delivery Date	10 units by Jan 1, 2000 (for SSDC & NRL testbeds)

† NOTE: A tradeoff is possible here as long as acceptance test criteria are met.
Comment: amplifier must be erbium. A description of the regenerator at each output port is needed since its spec is implied in the switch output port spec. This nominally would be electronic for Phase 1 and 2, and all-optic for Phase 3.

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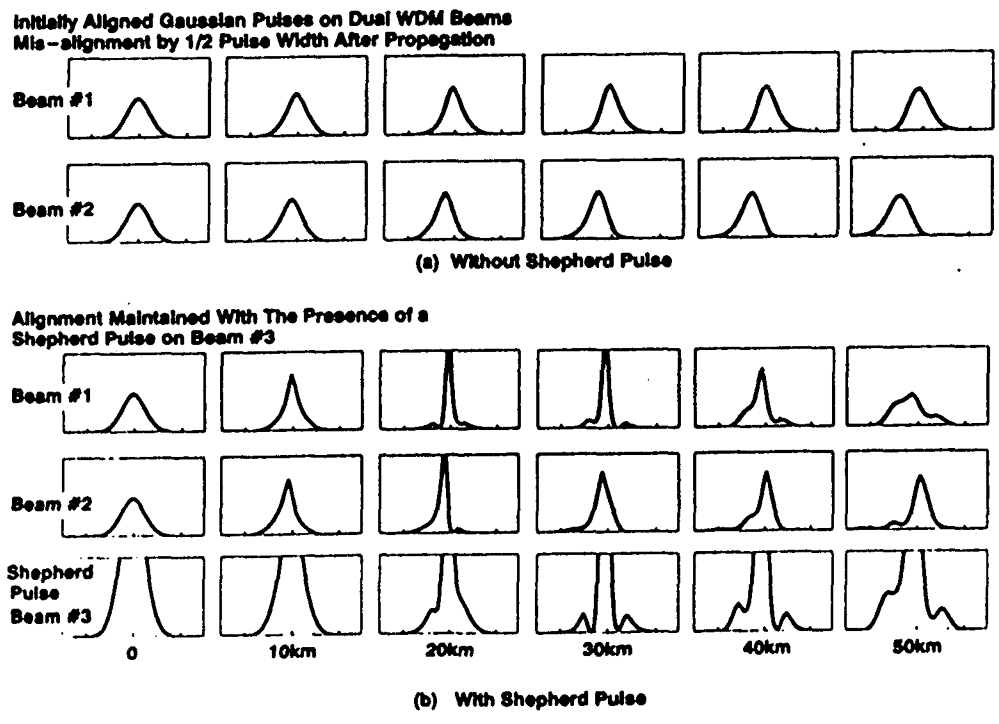

Figure 5 Evolution of two initially aligned gaussian pulses on two WDM beams. (a) After propagation, separation occurs for pulses on beam #1 and beam #2 without shepherd pulse on the third beam. (b) Alignment maintained for pulses on beam and beam #2 with shepherd pulse on the third beam.

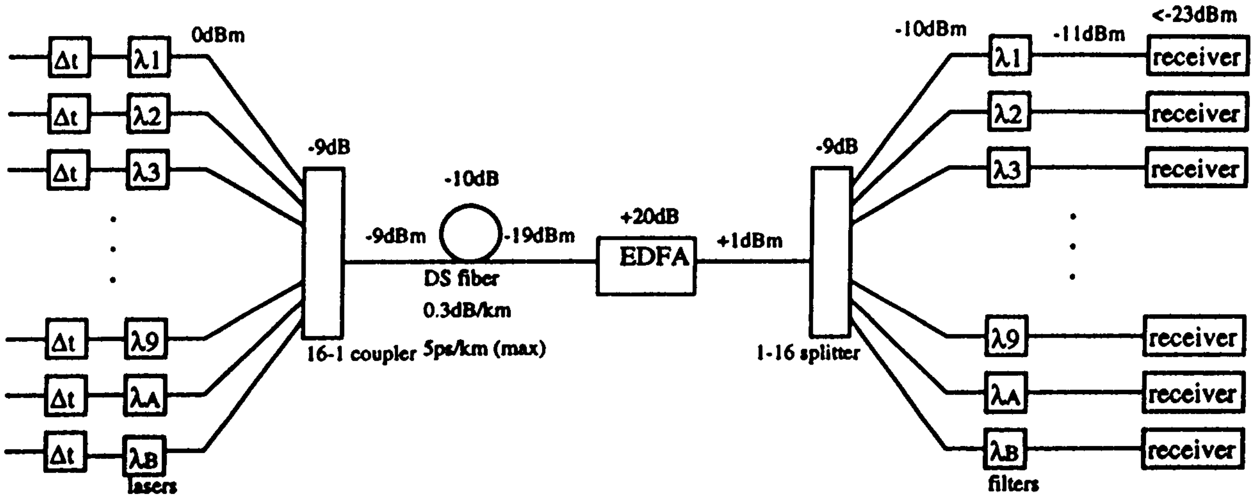

Figure 1: Block Diagram for an all-optical 12 channel bit-parallel WDM single fiber system

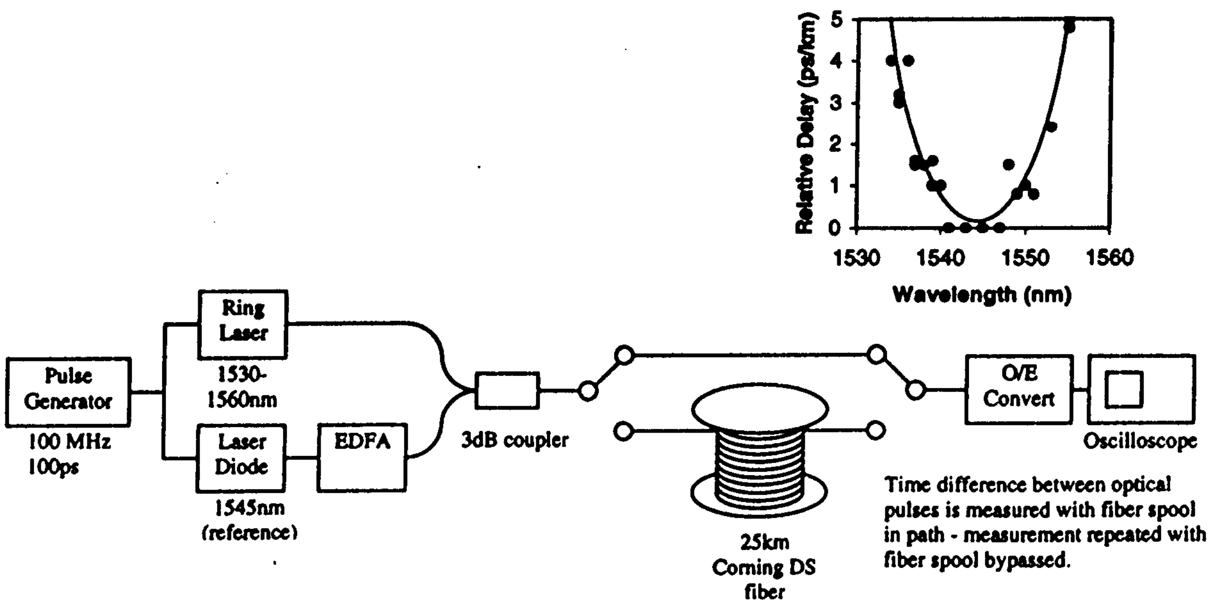

Figure 2: Measured group velocity differences for different wavelength beams. The sources are a tunable ring laser and a DFB laser diode at 1545nm.

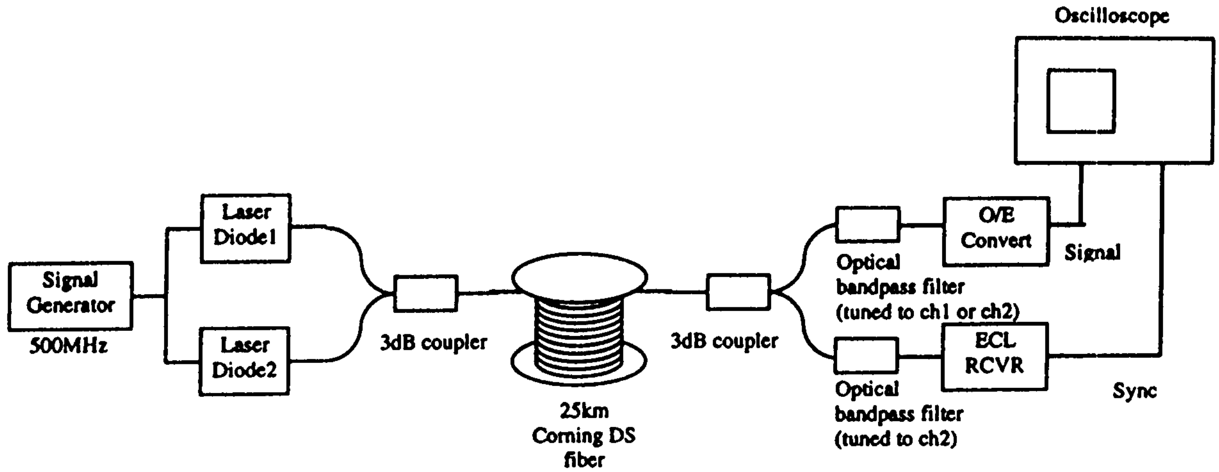

Figure 3: The experimental setup for the 2 wavelength bit parallel link

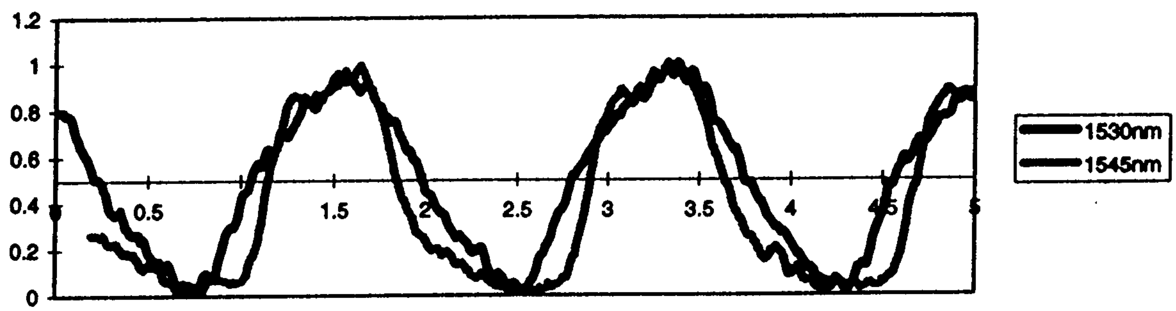

Figure 4 (a): A picture of the data channels before fiber input

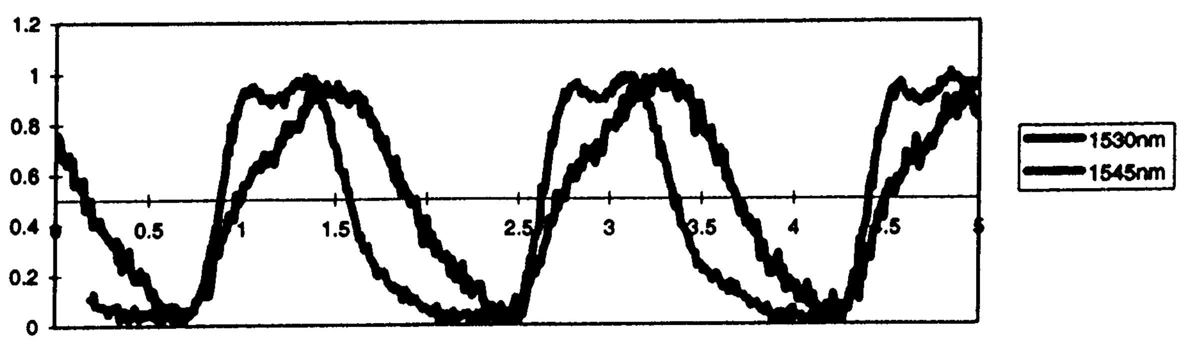

Figure 4 (b): A picture of the data channels after 25km of DS fiber